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SINGLE BEACON MID-COURSE GUIDANCE: EXPERIMENTAL PROGRAMME AND FURTHER DEVELOPMENT

by

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1 Introduction

In a previous technical note,[1] a system of intermittent beam riding mid-course guidance was suggested for a long range ground to air weapon. This note is intended to provide an interim report on the development of this system at the R.A.E., and to outline the scope of the investigation at present projected. Further comments are included on the countermeasure problem and the lines of future developments.

1.1 Outline of System

The system is based upon the use of a rotating radio beacon which specifies a bearing along which the missile or missiles must fly. This direction is called the datum line. The missile climbs to a certain height, after launch, according to a pre-arranged programme and equalises its height with that of the target on receipt of further information.

The datum line may continuously track the target in azimuth or may, initially, be directed at some future target position. A single beacon can be made capable of specifying 250 datum lines, at least, corresponding to 250 targets at a density of about 100 datum lines per degree.

In addition to specifying the line along which the missile must fly, information is also transmitted by the beacon which is used to align the homing head in the direction of the target.

The beacon consists of two transmitters with separate aerial systems. The first transmitter operates on X band and radiates a series of pulses at about 3200 p.p.s. from an aerial which has a polar diagram which is narrow in azimuth and roughly cosec^2 in elevation. The aerial rotates at the rate of one revolution in two seconds. The second transmitter operates on S band and transmits a short block of coded pulses whenever the X band transmitter aerial is pointing at a target. The coincident reception, by the missile, of the X band and S band signals, indicates that the missile is situated on the sight line beacon to target. Displacement in time of the S band signal with respect to the centre of the X band signal indicates to the missile its angular displacement from the datum line as seen from the beacon.

The block of S band coded pulses consists of 3 one microsecond pulses a . 5 half microsecond pulses. The one microsecond pulses carry the address code, which enables all the missiles destined for one target to select the transmission relating to their own group. The half microsecond pulses carry information on target height and on the angular position of the datum line in relation to its previous position. Pulse position modulation is used. The coded pulse block which relates to one target occupies 40 microseconds.

More detailed information on the operation of the system is contained in Ref.1, and further details of the equipment to be used in the experimental tests are given later in this note.

1.2 Purpose of the experiments

The experiments are designed to determine whether

(1) Datum lines can be specified, radiating from a beacon to an accuracy of one or two mils.

(2) The displacement of the receiving equipment from the datum line can be measured accurately for both small and large displacements.

(3) Datum lines can be moved in a manner similar to that expected if they were continuously directed at a target aircraft.

It is intended to investigate these points by equipping an aircraft with receiving and recording apparatus and flying this aircraft along approximately radial lines from the beacon. In the first and second parts of the experiments the true aircraft position will be recorded by the use of an air survey technique while recordings are made of the displacements from the datum lines obtained by the guidance system. If the results of this part of the experiment are satisfactory, an attempt will be made to fly the aircraft on a moving datum line to demonstrate that an interception course can be flown. Illustration of this will be provided by mounting a camera in the forward part of the aircraft, controlled in azimuth by the angular information transmitted by the beacon, so that the accuracy of the alignment of the centre of search of the homing eye defined by the guidance system may be checked. With such an arrangement the actual acquisition of the target by an A.I. equipment mounted in the guided aircraft could easily be demonstrated.

These trials will involve fairly detailed checking of the design of the transmitting equipment. This is thought to be necessary, particularly with regard to the X band aerial characteristics. The specification of this aerial is unusual in that a high degree of symmetry is called for in the shape of the sides of the main lobe, and although the contractor will no doubt obtain this symmetry in the aerial as measured on the factory test site, the effective polar diagram may be slightly modified by the peculiarities of the site chosen for the beacon.

Apart from demonstrating in a practical manner, by the construction of a simplified prototype beacon that a rotating beacon of this type is feasible and that the processes of data handling, code generation and transmission are possible, various propagation effects which are impossible to calculate accurately need to be investigated. As well as the site effects mentioned above which can lead to inaccuracies by apparent beam distortion, the depth and frequency of fading is important. To minimise this effect the transmitting aerials have been specified to have a rapid fall off of signal at elevations below 1^{o} and provision is made for small variations to be made in the angle of elevation of the X band aerial, so that the proportion of signal directed at the ground and capable of causing fading by reflection can be varied.

In this connection it should be noted that two sites will be used in the experiments. Most of the work will be carried out from a site situated at Ewshot, near Farnborough, where the beacon will be effective over a south westerly or a south easterly quadrant, which will provide information on the propagation difficulties likely to be experienced over land. In the summer of 1957, the equipment will be transferred to a coastal site on which a long range surveillance radar is available, which can be adapted to provide target bearing information in the correct digital form, to enable propagation effects over sea to be investigated, as well as interception courses to be flown.

2 Equipment for Experimental Programme

A detailed account of the ground and airborne equipment, which is to be used in the experimental programme, will be given in later technical notes. An outline description of this equipment is given below.

For the experimental trials, it has been decided that while the S band transmitter should be capable of transmitting the codes for 250 targets (a minimum capacity of 50 has been specified), the target simulator to be used and the data handling channels need only be capable of handling information on 3 targets. The reason for this is that the problems involved in making

the transmitter handle a large number of channels are relatively small, while the quantity of equipment involved in handling information on a large number of targets is great. However, all the tests necessary for examining the potential accuracy of the system can be carried out with a maximum of three target channels in operation. On completion of the trials, however, the transmitter will be capable of operation with more complicated multi-channel data handling equipment, if it is considered that the development should proceed further.

Ground radars such as the future developments of Orange Yeoman are unlikely to be able to provide target bearing information to an accuracy better than 11 or 12 digits. The beacon, however, is to be designed to produce bearing information to 13 digit accuracy and it is intended to use all 13 digits in obtaining coincidence with target bearing. The target simulator is designed to give bearing to 13 digits, the first three of which (the most significant) are fixed. In operating with a radar it is intended to describe target bearing to 13 digits even though the last two digits (the least significant) may have no significance.

The use of 13 digits can be justified in the experimental equipment on the grounds that:-

(1) The experiment is designed to show the limit of accuracy of this method of guidance. Using currently available techniques, the specification of aerial bearing to 13 is near the limit of the methods available.

(2) The missile navigation problem can be eased by minimising additional errors introduced by the mid-course guidance system and the specification of bearing to this accuracy enables smooth extrapolation of datum line position to be made between radar plots.

(3) Target data may be derived in some weapon systems from radars capable of providing greater accuracy in bearing than Orange Yeoman, e.g. tracking radars. In this case it would be desirable to make the errors introduced by the beacon as small as possible.

2.1 Shaft Coder

This equipment is being made by Messrs. Hilger and Watts. Two equipments will be constructed, one for incorporation in the interim X band aerial mounting and one for the final X band aerial mounting.

It is necessary to maintain a continuous record of the bearing of the X band beacon aerial beam from a reference direction, and it is desirable that this record should be to an accuracy better than 1 practical milliemo. This bearing must be presented in a binary digital form capable of direct comparison with the digital number for target bearing. It is thus necessary to compare 13 digits. This means that the angular rotation of the aerial between the digits is 0.78 practical mils. Thus if the aerial driving shaft rotation is described to 13 digits, the position of this shaft can be known to ±0.39 mils. This accuracy is satisfactory provided that there is a minimum of flexibility in the shaft connecting the actual aerial and the coding device.

A glass coding disc is mounted directly on the vertical aerial shaft which rotates in bearing with a revolution period of two seconds. The glass disc is inscribed with three graduated annular tracks and a light beam is focussed on the disc and interrupted by the graduations. A photocell is mounted below each track.

The photocell under the first track receives one pulse of light every 0.78 mils of rotation. The output of this photocell, after suitable shaping is used to drive a scale of two counter representing bearing from some fixed reference line.

The reference line of the disc is defined by the second scale which permits only a single pulse of light to pass through it. This pulse is used to reset the bearing counter so that, after each revolution of the disc, the bearing count will always be correct with respect to the disc reference line.

A mechanical adjustment is necessary to allow the reference direction of the disc to be aligned with a given bearing.

A third scale on the disc is used to provide 6,400 pulses per rotation which, after suitable shaping, are used to trigger the modulator of the X band transmitter. This ensures that the X band transmitter transmits one pulse for every practical millieme of rotation of the aerials.

2.2 Coincidence detection and data handling

The whole of this equipment, including the target simulator, is being constructed by Messrs. Ericssons. The equipment compares each target bearing with the beacon bearing, and determines the change in the angular bearing of the target from the bearing in the previous scan. Each coincidence of target and beacon bearing results in the generation of a channel trigger pulse which releases data relevant to the particular target, to a digital store system so arranged that the data is ready for translation to the transmitted code. Target height is included and will be coded and transmitted in order to complete the transmission. It will be preset in the experiment, however, and will be received and recorded but not decoded. It is ultimately intended that azimuth coincidence of targets will result in target data being transmitted in range priority, velocity priority or a combination of the two, but in this equipment, the order of transmission is decided in an arbitrary manner.

For convenience, in the experimental trials period, a target simulator will be provided, capable of providing simple tracks on up to three targets.

The items to be constructed comprise:-

(1) A comparator and difference unit.

(2) A store, code converter and switch unit.

(3) A target course simulator.

The comparator and difference unit accepts azimuth information from the beacon coder unit and each target track of the target course simulator. It provides an output at each coincidence of beacon and target bearing.

This unit is also required to provide at each coincidence between beacon and target azimuth, in each channel, the change in target bearing since the last coincidence was established.

The coincidence pulse obtained from this unit is used to transfer the difference angle data to the output register, and to trigger the address code generator and code converter at the correct times. The data is handled in such a manner, that there is no possibility of a coincidence being missed or of a false coincidence being generated.

The code converter and [illegible] unit converts the target data from binary form, representing height and bearing difference angle, into a form that may be used to establish a pulse position code. Three separate channels are to be provided to allow for three independent target tracks. The output signals from these three separate channels are to be combined in time sequence on a common set of output leads.

A set of leads are provided for the bearing difference data and another set for height data. Each output is allocated a different quantum level in the data to be transmitted and the correct lead is sequenced and pulsed. The output code indicates bearing difference in 31 quantum levels (+15 to -15) and height in 63 quantum levels, each quantum representing a 1000 ft height zone. A 32nd quantum level in angle and a 64th quantum level in height are available for transmission monitoring purposes.

The target simulator takes the place of the radar and auto tracking unit, presenting target bearing data to the comparator and height data to the code translator. Only simple target courses are required. Target bearing is specified in binary digital form to 13 digits. The first 3 digits will be preset into the simulator restricting the sector of operation to 45°. The courses to be simulated are:-

(1) Constant bearing courses on all three tracks.

(2) Courses having a constant rate of change of bearing, either positive or negative in sign, the rate of change being controlled by manual preset between limits of [illegible] quanta/second for 2 tracks, the third track being fixed.

2.3 Code Translator

This unit has been designed at R.A.E. and is under construction. It will convert the data produced by the code converter of the Ericsson equipment, in the form of pulses on particular leads, to the correct pulse position code for the input of the modulator of the S band transmitter. It will also generate the address codes allocated to each channel.

The generation of the pulse codes is controlled by a 2 mc/sec crystal oscillator followed by a gate which admits, to the translator circuit, a train of 80 pulses each time a coincidence is established. By the use of a series of binary dividers and a diode network, keying pulses are applied sequentially to 23 gate circuits. Two of these gates are opened by each line marked by the code converter so that for the address, angle and height codes a total of 6 gates are opened. In addition fixed marker pulses are admitted to each code. The outputs of the gates are combined in two groups. The first five gates, together with the first marker pulse provide the first group of three pulses which are shaped to be 1 microsecond long. The second marker pulse and the outputs of the last 23 gates are the second group of five pulses which are shaped to be ½ microsecond long. Both groups are then combined and fed to the modulator.

2.4 Transmitters

The transmitters are being constructed by B.T.H. and will be available in the summer of 1955. An improved X band aerial and transmitter will be made available six months later.

The first or interim X band transmitter will use a modified marine radar aerial producing a 1.2° beam in azimuth and horizontal polarisation. This will enable experiments to commence and the operation of all other equipment to be perfected before the final X band aerial is available. It will also enable a comparison to be made of the effects of fading with horizontal and vertical polarisation, which will be available on the final aerial. The final X band transmitter will have a 0.6° beam in azimuth and more sophisticated shaping in the vertical plane. In particular, it will produce a sharp cut off at elevations below 1° to minimise the intensity of the ray directed at the earth's surface and thus, it is hoped, the effects of fading will be reduced.

Because the aerial of the final transmitter is more than twice the size of the interim aerial, the marine radar drive would not be powerful enough to rotate it. Two different mounts are therefore being built. The transmitters used will have the same characteristics in each case:-

Peak power 100 Kw, or at least more than 50 Kw.
P.R.F. 3200 p.p.s.
Pulse duration $\frac{1}{2}$ microseconds.
Aerial rotation 30 r.p.m.

The modulator, in each case, will be driven from the output of the third track of the shaft coded disc, so that one pulse will be transmitted every mil of aerial rotation.

The aerial structures and mounts are required to have a torsional stiffness of better than one mil. The aerial will be equipped with a telescope mounting for alignment purposes.

It was originally intended that the S band transmitter would have an azimuthal beam width of 40° and would be rotated in synchronism with the X band aerial. However, it was found that to obtain the desired fall off of power at low elevations to minimise fading, it was necessary to construct an aerial 17 feet high. Although this aerial could have been rotated at the desired rate, it was decided that since the operation of the system was not dependent upon this feature, it would be abandoned in the experimental equipment and made semi-fixed. The main advantage of rotating the S band aerial would be that a polar diagram narrower in azimuth could be used, with a correspondingly increased field strength at the receiver, and consequently a slightly better resistance to jamming signals.

The S band aerial under construction is 17 ft high and $3\frac{1}{2}$ ins wide giving an 80° wide beam with a shaping in the vertical plane the same as that for the final X band aerial. Polarisation will be vertical. The aerial will be capable of rotation by hand so that the sector of operation can be changed but normally it will remain fixed in one position, the wide angle coverage in azimuth allowing sufficient latitude for the trials.

The transmitter will be capable of providing a signal of 5-10 Kw peak, driven by a hard valve modulator and will be capable of handling at least 50 consecutive coded blocks. The modulator will be fed from the code translator.

2.5 Airborne Equipment

This equipment has been designed at R.A.E. and is under construction. As far as possible standard equipment and techniques have been used.

The equipment consists of two separate receivers, one on X band and one on S band. The outputs of the two receivers are combined in the angle measuring circuits. The measuring circuits are triplicated to allow simultaneous reception of signals relating to all three channels.

Each receiver is fed fro[illegible] horns mounted in the tail of the aircraft (a Varsity). Measure[illegible] can only be made on outward radial courses. The polar diagrams o[illegible] aerials is such that coverage in elevation can be from 0° to -2[illegible] in azimuth to ±30° to half power points.

The receivers are being [illegible] tunable over a small range of frequency so that adjustments [illegible] made to cover slow drifts in the frequencies of the ground trans[illegible]ers. No facilities will be made for A.F.C. in the experimental equ[illegible] but the bandwidth of each I.F. will be made approximately 10 Mcs/s[illegible] preserve pulse shape and to allow for some degree of frequency drif[illegible] long period A.G.C. system will be used which retains the A.G.C. [illegible] developed for 2 seconds until the next signal has been complete[illegible]ived and a new A.G.C. voltage is developed.

After the reception of t[illegible] signals, a blanking pulse of 1.5 seconds duration is applied to the rece[illegible] to prevent the reception of unwanted signals. In an operational equ[illegible]t this blanking pulse would be extended to about 1.9 seconds to provide [illegible] protection. This is not possible in the experimental equipment be[illegible] of the provision made for three channel reception through one re[illegible], since the S band transmissions can be widely separated in tim[illegible].

The 1 microsecond pulses [illegible] the address code of the received S band message are passed to a delay [illegible] with taps every microsecond. The taps on the line are connected to thre[illegible] "and" gates, corresponding to each channel, in such a way that thre[illegible] taps are connected to each "and" gate. The correct spacing of the addre[illegible] pulses causes a pulse to be obtained from the appropriate "and" gate which generates the correct waveforms for the display unit[illegible] triggers the angle counters corresponding to that channel.

Initially, it is not inten[illegible] decode the angle and height codes but only to display the received codes on a cathode ray tube and to record them photographically. At a later stage, decoding equipment for at least the angle code for one channel will be introduced.

Channel trigged pulses, derived from the S band signal, are fed from the receiver "and" gates mentioned above to each angle counter. The de[illegible]dulated X band pulse train, suitably amplitude limited, is fed to all th[illegible] angle counters in parallel, through an p.r.f. selector.

For each channel there is both a fine angular error counter and a coarse angular error counter. The fine counter is used when the S band pulse for that channel is received at the same time as the X band pulse envelope is being received, and the coarse counter is used when the S band pulse falls outside these limits.

2.51 <u>Fine angular error determination</u>

The problem of finding the relative position of the X band received signal to the S band signal when the angular error is small (i.e. the navigation error) involves the addition and subtraction of received X band pulses above a threshold level and the display of the result in a suitable form. Initially, there is no intention of navigating the aircraft accurately from the error signals, and so the conversion of these results to a suitable analogue form does not arise until attempts are made to fly interception courses. A display is necessary for recording and as a pilot indicator. The display for recording will depend upon the photography of dekatron counters while the pilot indicator will consist of indicator bulbs showing when the aircraft is not within the limits of the fine angular counter and the sense of the error.

A circuit to carry out this addition and subtraction has been devised using a reversible dekatron counter consisting of two scales of ten. Provision is made for adding or subtracting up to 50 pulses. This is to allow the counting system to cater for a polar diagram of greater width than optimum and to allow for the inability of the A.G.C. circuits to correct for changes in signal level over the 2 second period. Rapid changes in signal strength could result in the level of acceptance in the X band receiver limiter varying from between 3 db below the peak of the signal to about 15 db below the peak and the consequent admission to the counter circuits of a longer block of pulses.

2.52 Coarse angular error determination

This unit measures the time from the reception of the S band pulse to the centre of the X band pulse train or vice versa when the S band pulse falls outside the limits of the X band pulse train. The unit measures the value of this error up to ±320 mils and displays the result as a count on three dekatrons together with a neon indicator to show the sense of the error. It should be noted that since this angular error is obtained by timing the reception of the two signals it is dependent upon the beacon aerial rotating at a constant rate and any variation in rotational rate is reflected as an error in this angular measurement. The limit of variation of beacon rotational rate is 5% and an error of this magnitude is of no consequence in the coarse angular measurement.

This is not true of the fine angular measurement as in this case the accuracy is independent of beacon rotational speed, provided that the p.r.f., which is controlled by this rotational speed, is within the limits of the receiver p.r.f. selector.

3 Technique of experiments

It has been estimated that the guidance system proposed should enable a receiver in an aircraft to estimate its position from a given transmitted datum line to an accuracy of between 1 and 2 mils peak neglecting errors due to site and propagation effects which are impossible to forecast. If it is assumed that the measurement will be accurate to 1 mil, this corresponds to an accuracy of 50 ft in plan position at 10 miles from the beacon to 500 ft at a range of 100 miles. To examine these errors properly, a method of measurement of aircraft position is required which gives an accuracy approximately an order of magnitude better at the more important ranges i.e. about 100 miles range.

There are two readily available methods by which aircraft position can be measured to an accuracy of 50 ft in plan. The first method involves the use of a tracking auto-follow radar sited at a surveyed point on the ground, 100 miles from the beacon. This method was discarded as it suffers from several obvious limitations:-

(1) At the height at which the aircraft will be flying i.e. about 10,000 ft, currently available auto-follow radars would only be able to provide measurements to the required accuracy when the aircraft was within about 5 miles. To cover the whole of the radial flight of the aircraft many radar sites would be required.

(2) The establishment and maintenance of any radar sites for this purpose would be expensive in manpower and equipment.

(3) Presenting the results of the radar tracks in the desired form would be tedious and difficult.

(4) Co-ordination of recording would be required at beacon, aircraft and radar sites.

(5) The area of operation would be limited by the availability of radar sites. This would make the investigation of beacon site effects very difficult.

The one advantage that this method might have is the relative freedom from weather restrictions.

The preferred alternative method involves the use of air survey techniques.

In this method the aircraft position is measured by inspection of a series of aerial photographs taken from the aircraft of the terrain over which it is flying. To obtain the position of the aircraft when the photograph was taken, requires the use of a technique which is the reverse of that used to obtain maps from aerial photographs. It is claimed that in this way, the position of the aircraft, in plan, can be obtained to an accuracy of better than 50 ft (peak error) without any special precautions, such as the use of a stabilised camera mounting. The limit of peak error can be $\frac{\text{height of aircraft}}{1000}$.

Arrangements are being made to fit a standard air survey camera in the Varsity to be used in the trials and a series of overlapping photographs will be taken in flight at the rate of 1 per mile (for an aircraft flying at about 10,000 ft). Provided the aircraft is flying over terrain with distinctive markings, the developed photographs can be projected by a pair of projectors, and the positions of the projectors adjusted so that exact coincidence is obtained on the portions of the pictures which overlap. If the projector of the first image is adjusted to obtain exact coincidence of the image with an ordnance map of the area, the positions of the projectors will bear the same relationship to the projected picture, as the aircraft bore to the ground when the picture was taken. By measuring the plumb point of the projector and referring to ordnance maps, the position of the aircraft at the instant at which the photograph was taken can be determined accurately, and a graph can be drawn depicting the deviation of the aircraft from any reference line against time.

The Varsity will be operated at its normal cruising speed of 270 ft/sec and one photograph will be taken every 22 seconds i.e. approx. 1 per mile. The reference lines to be chosen will be radial lines from the beacon and the results after analysis will depict angular deviation of the aircraft, as seen from the beacon, in mils, against time. This will be compared with the records obtained from the apparatus recording the outputs of the guidance equipment.

The "reverse" air survey technique is completely developed and a contract is being placed with the Air Survey Co. of White Waltham to carry out the plotting of aircraft position in the manner described and to provide various auxiliary services in connection with this part of the experiment.

The method has numerous advantages such as allowing complete freedom of operation of the aircraft but it suffers from two important and obvious disadvantages. Firstly, the method is useless over sea, and secondly, good visibility is required to obtain good aerial photographs.

It is intended, therefore, that all measurements connected with the accuracy of navigation will be conducted with the aircraft over land, except for the final interception trial. The visibility restriction will limit experimental work to days when the cloud below 12,500 ft does not exceed $\frac{1}{8}$th and the surface visibility is about 10 miles. It is likely that on a few days each month the conditions will be satisfactory.

3.1 Recording equipment

It is convenient at this stage to summarise the items which will be recorded in the trials. In the aircraft, there will be three cameras. These will be:-

(1) The air survey camera recording at 1 frame every 22 secs.

(a) Ground position.

(b) A serial number for this photograph.

This camera also generates a pulse which

(a) Moves on one place, number counters in the other two aircraft cameras.

(b) Generates a 1000 c.p.s. tone pulse which is transmitted over the V.H.F.

(2) The counter recording camera recording at 1 frame every 2 seconds.

(a) Three dekatrons registering coarse angular error on three channels. Total 9 dekatrons.

(b) Two dekatrons registering fine angular error on three channels. Total 6 dekatrons.

(c) Two dekatrons operating from 10 c.p.s. generator giving the time elapsed since the last air survey photograph was taken. Total 2 dekatrons.

(d) A number counter showing the serial number of the last air survey photograph.

(e) Six neons showing the sense of the error of each coarse angular count.

(3) The oscilloscope recording camera recording on continuously moving film.

(a) A trace of each received angle and height code, the trace for each channel occupying a different lateral position on the tube face.

(b) The level of A.G.C. voltage on the X and S band receivers, displayed by displacing the spot on the cathode ray tube in the intervals between the display of (a).

(c) A number of counters, illuminated by a flash tube, showing the serial number of the last air survey photograph.

On the ground, recordings are made on the beacon. Height and bearing of one datum line are fixed for each run and are set by keys. Two datum lines are moving. Recording is made on a 22 pen recorder, recording on Teledeltos paper. The following items are recorded:-

(a) The 10 least significant digits of the bearings of the two moving datum lines.

(b) On the 21st pen, a mark recording the receipt of the 1000 cps pulse over the V.H.F. indicating operation of the air survey camera.

(c) On the 22nd pen, a mark is made every second, controlled by a clock pulsing unit.

It is thus possible to relate any part of any record with the data recorded at the same time on any other recording instrument and to obtain interpolated measurements with a reasonable degree of accuracy.

3.2 Experimental method

The aircraft will fly at 12,500 feet for most of the experimental work. At this height the cameras available provide a negative which can be easily projected with existing equipment to fit a standard ordnance map scale.

In the first experiment, one datum line will be transmitted on a convenient bearing say S.W. from Farnborough. The pilot of the aircraft will be asked to fly on this radial course as accurately as possible assisted by indicator lights operating from the angle measuring circuits. From the analysis of the air survey plots and of the dekatron photographic records, two records will be available of the angular displacement and variation of the displacement from the datum line bearing from the beacon. This will be repeated on several bearings.

The second step will be to fly the aircraft along a radial course such as that above, now moving the other two datum lines through the fixed one at various rates and with them moving both in the same and in opposite directions. This will enable a check to be made of the accuracy of the coarse error circuits, the accuracy of error determination when changeover is made from fine to coarse circuits, and the possibility of interference between different channel codes when they are transmitted in rapid succession. In all these trials the recordings of A.G.C. levels in both receivers will indicate the rapidity of fading and the records of the angle and height codes will enable the difficulties of decoding these trains to be assessed.

If good agreement is found between true aircraft position and the position estimated by the guidance equipment, the use of air survey becomes no longer essential.

In the third series of trials, an attempt will be made to navigate the aircraft on a moving datum line, the rate of movement being made compatible with aircraft speed, manoeuvring ability and pilot reaction time. This will conclude the series of measurements carried out with the beacon at Farnborough.

It is considered important that some trials should be carried out while the aircraft is flying over sea. To do this it is proposed to erect the beacon at a suitable coastal site, and to carry out trials:-

(a) To test for any site peculiarities.

(b) To investigate fading over sea.

This will clear the way for a full scale demonstration of the system involving an interception. To enable this to be done some additional development will be necessary.

(i) Decoding of angle needs to be completed.

(ii) A moveable camera mount actuated by angle information will have to be fitted in the aircraft.

(iii) A suitable A.I. or homing head may be fitted to the aircraft.

(iv) Equipment needs to be made available to enable target bearing to be extracted from a long range radar say type 80, for one target, and fed in binary digital form to the beacon.

This trial would demonstrate the accuracy to which the centre of scan of the homing could be aligned on the target.

4 Vulnerability to R.C.M.

In GW Tech. Note 347, it was concluded that to jam the mid-course guidance system effectively, selective (tuned) jamming was necessary, and that wide band noise radiated by the target was ineffective. The possibility of using more sophisticated jamming, aimed at braking through the code system was mentioned. Such jamming might consist of the radiation of pulses, at regular times.

It had been assumed that in an operational system the receiver circuits would be designed incorporating precautions against jamming in the intervals between the reception of beacon signals, by suitable gating circuits.

It is, however, quite evident that using only the most elementary precautions, the mid-course guidance is likely to be more difficult to jam than the ground radar or the homer.

4.1 Jamming of S band transmission

Jamming of the S band transmission might be attempted from the target by noise, transponder, pulse trains or irregular pulsed transmissions.

4.11 Noise

It has been shown previously, that to jam the S band communication link to the missile at a range of 10 miles, when the target is 150 miles from the beacon, requires a jammer power output of about 760 watts, where the transmitter peak power is 10^4 watts, the ground transmitter aerial gain is 75, the front to back ratio of the guidance receiver aerial is 10 and the jammer aerial gain is 10. (A jam power/signal power ratio of 0.2 is assumed to cause jamming.)

This level of power could not be radiated over a wide range of frequencies and would probably be obtained by noise modulating a selectively tuned jammer. To be certain of jamming the correct transmission, a panoramic receiver system would be required with a look through device. It is evident that a fairly complicated jamming system is required radiating a high mean power and that the level of power would be at least an order of magnitude higher than that required to jam the ground radar.

It is worth noting in passing that the values of the guidance system parameters chosen for this illustration are by no means near the limit of what might be obtained. In particular if a transmitter valve were specifically designed for this application a power output of at least 10 times and possibly 100 times the value assumed might be expected.

4.12 Transponder

One type of jammer likely to be met in the next decade is the transponder or repeater jammer. Suppose such a jammer situated in the target, repeated the codes received by it in the general direction of the beacon, suitably amplified with zero delay.

The total length of the coded message is 40 microseconds and since the missile will be situated between the beacon and the target, if the distance between the missile and the target exceeds 4 miles, the missile would receive the whole of the message from the beacon before it received the relayed signal from the jammer. On receipt of the beacon message the missile receiver would be closed down until approx. 1.9 seconds later. The jammer signal would thus be ignored.

Missiles attacking other targets would ignore these repeated transmissions because the address codes would be incorrect. The only way in which the transponder type jammer could hope to interfere with the proper operation of the guidance system would be by delaying each repeated transmission by nearly two seconds so that it was received by the missile just before the next beacon transmission reached it. This would involve a very complicated type of jammer and such jamming does not seem to be very feasible.

4.13 Pulse trains

It is clear that the transmission by the target of a regular series of S band pulses of 1 : 1 mark space ratio, the pulses being 1 or ½ microseconds long would cause inoperation of the address or information decoding circuits. However, for this type of jamming to be effective it is evident that the power to be transmitted by the jammer needs to be comparable with the power required for effective jamming by noise. It is also necessary in this case for the jammer to be tuned exactly to the beacon frequency.

Under the conditions given above the peak power required from the jammer to produce pulses equal in amplitude to the beacon transmission is 3.8 Kw, with a mean power of 1.9 Kw. This is only sufficient to interfere with the coding systems at a range of 10 miles and normally a missile at this range would be expected to be operating on homing.

A more economical way of using pulse jamming would be to transmit pulses at longer intervals.

4.14 Irregular Pulses or lower frequency pulse trains

If the jammer radiated one pulse, one microsecond long every [illegible] microseconds or one half microsecond pulse every 13 microseconds, it could be sure that one of these pulses would occur during the reception period of similar pulses in the beacon message by the missile. It would be necessary to transmit rather more frequently than this to ensure that this additional pulse was not received in coincidence with a message pulse.

The peak powers required would be the same as that given in the previous section with a reduction in the mean power dependent upon the mark space ratio.

Consider first the effect of an additional pulse received by the missile during the reception of the address code. This missile still correctly recognises the address code and ignores the additional pulse. It is possible, however, that two other sets of missiles destined for other targets could decode this address accidentally if within range of the jammer and could incorrectly acquire the information code relating to this message. This would be of no assistance to the jammer aircraft as the missiles destined for it would still be receiving the correct information. There are certain unlikely exceptions to this state of affairs, such as if the three pulses of the address code are equally

spaced and an interfering pulse is received an interval in front of the first marker pulse, equal to the interval between address code pulses. In this case the address would be decoded early, but as the first half microsecond marked pulse would not appear at the correct time the information in the message would be ignored. This could introduce an error in the alignment of the centre of the homing eye search of 11.7 mils maximum. Such a big error is unlikely and even so is probably unimportant if the occurrence is rare.

Another exception occurs when there are several targets. If the jammer transmits an additional pulse which is inside the transmission of another address code, it is possible that a code could be produced which would be identical to the address code of the missiles attacking the jammer. This could result in the missile which received the jammed address code deducing its displacement from the datum line incorrectly and decoding incorrect height and angle information.

A better alternative for the jammer would be to transmit $\frac{1}{2}$ microsecond pulses more frequently than once every 13 microseconds with the intention of interfering with the information portion of the message. These pulses would not affect the address. The same rules for calculating jamming power apply here as to the address code.

The first part of the information code refers to the change in datum line bearing. Thirty one levels can be transmitted, covering quantum levels from -15 through 0 to +15. Since the interfering pulse could not be phase locked to the message transmission the pulse would occur at random times. If it was received by the missile before the second of the two correct pulses a false angle value would be received, it it were received after or not at all, the correct message would be decoded. The code might be so arranged that a false angle value is as likely to be positive as negative. This would help to reduce the seriousness of the cumulative error produced by this form of jamming.

A series of $\frac{1}{2}$ microsecond pulses would similarly lead to the incorrect decoding of height information.

More complicated codes can be devised and the possibilities will be discussed later.

4.2 Jamming of the X band transmission

Jamming of the X band transmission is likely to cause errors in navigation. It was shown[1] that noise jamming at a higher power level was required to jam this transmission than that required to jam the S band transmission. Furthermore unless the jamming is very intense the error in navigation will be small and of little significance. This coupled with the fact that the jammer difficulties are increased as λ is decreased, for equal power radiated, suggests that jamming of this transmission by noise is unlikely.

The possibility still exists that pulse jamming may be attempted. The experimental receiving equipment requires the X band train to consist of at least 2 pulses separated by the correct interval ±15 microseconds. This is to exclude the possibility of the equipment being incorrectly triggered by a stray pulse on the same frequency, say by a radar pulse. This interference rejection circuit in an operational weapon system would be extended so that a minimum of 10 pulses at the correct spacing would be required to cause operation.

Also, in the experimental system, the receiver will be ready to accept a new signal 1.5 seconds after the reception of the S band signal. In an operational system the receiver would not be made ready to accept fresh pulses at a fixed time interval after the reception of the S band signal, but at a variable time depending upon range. For example, when the missile was being gathered to the datum line and was close to the beacon the S and X band signals might be received fairly widely spaced and the receiver might need to be open to receive fresh information 1.5 seconds after the last signal. As the range increased the missile would stabilise on the datum line and the receiver would not need to open to receive fresh information until at least 1.9 seconds after the receipt of the last information.

A pulse jammer would need to have the following characteristics, therefore:-

It would need to transmit at least 10 pulses at a time at the correct p.r.f. at least once every 0.1 seconds, at a power level to induce a signal in the missile comparable with the beacon signal. To produce signals of equal amplitude the power required P_J would be

$$P_J = \frac{P_T \cdot G_T \cdot g_m \cdot d_1^2}{G_J \cdot d_2^2} \qquad \text{See Ref. 1 page 24.}$$

If $P_T = 10^5$ watts, $G_J = 10$
$G_T = 5000$, $d_1 = 10$ miles
$g_m = 10$, $d_2 = 140$ miles

we have

$$P_J = \frac{10^5 \cdot 5000 \cdot 10 \cdot 10^2}{10 \cdot 140^2} \text{ watts}$$

$$= 2.5 \text{ megawatts.}$$

The mean power level would be 250 watts.

This would jam the X band receiver at 10 miles range and approximately 4 times this power would be required to jam at 20 miles range.

Since this equipment needs to be accurately tuned to the beacon frequency it does not appear to be a very probable form of airborne countermeasure.

Apart from the obvious counter countermeasure gambits one of the most effective measures would be to reduce the open period of the receiver to a minimum to force up the rate at which the jammer had to radiate the pulse blocks and hence to raise the mean power level.

4.3 Reduction of R.C.M. vulnerability

The methods of transmission proposed for this guidance system are extremely wasteful of bandwidth and in this sense cannot be considered to be optimised properly. The selection of the methods chosen has been determined on the grounds of practical expediency as, in general, a more refined transmission system would have demanded valve development, or more complicated circuit development.

The reduction of the countermeasure vulnerability must be divided into two parts and the X and S band channels considered separately.

4.31 X band transmission

The X band transmission proposed involves the transmission of one pulse for every practical millieme of aerial rotation. Variations in aerial rotational speed over short periods are unimportant when the receiver is close to the datum line as the receiver determines its position in the beam by counting pulses. A C.W. transmission could be used instead of a pulse transmission[2] but in this case the receiver would have to determine its position by timing on the signal envelope, assuming a fixed rate of rotation of the aerial.

If the transmission was a C.W. one, the bandwidth of the receiver required would have been a few kilocycles per second. For transmission of equal mean powers, a reduction in the vulnerability to noise barrage jamming would be obtained. However, since receiver A.F.C. is extremely difficult to obtain in an intermittent transmission of this type, the advantage of such a narrow bandwidth could not be properly exploited without a great deal of receiver complexity. To enable A.F.C. to be dispensed with, a bandwidth for the receiver of about 10 Mcs/sec is necessary, to allow for drifts in the transmitter and receiver frequencies. In the transmission proposed, ½ micro-second pulses will be transmitted which are more compatible with the band-width necessitated by the frequency drift requirement.

Recent simulator work has shown, however, that there is a possibility of producing a workable system with a data rate as low as 10 seconds. This immediately opens up the possibility of dispensing with the X band portion of the beacon and making use of the surveillance radar beam instead. There are certain difficulties in doing this and it is proable that the accuracy of navigation will suffer slightly. One advantage of this possibility, from the R.C.M. viewpoint, is that the p.r.f. could be made more stable and the p.r.f. selection could be made more effective.

It is interesting to note that a pulsed rotating beam operating at a p.r.f. of 3200 p.p.s. would probably be assessed by an intercept unit as a short range surveillance radar, whereas a rotating C.W. beam is likely to arouse more interest.

The accuracy of navigation is not much affected by the use of a pulsed or C.W. transmission, and the final choice between the two possibilities in an operational system would be based on transmitter valve availability, in that the power output and frequency stability would have a direct bearing upon the counter-measure resistance of the system.

4.32 S band transmission

The reduction of the susceptibility of the S band link to counter-measures is a more complicated problem.

The code could be improved to reduce bandwidth, to alter target saturation possible on any one bearing by decreasing the time required for each message, or to increase mean power in each message period possibly at the same time incorporating some measure of redundancy. The present saturation density of 100 targets per degree may be higher than necessary and it might be possible to reduce this to allow longer pulses to be used and the bandwidth to be decreased. This would have the effect of increasing the average power required per beacon data period. However, the bandwidth of the receiver is again determined by the requirements set by frequency drift.

The best solution would appear to be offered by the use of a code containing redudant information coupled with a general increase in mean power, so that the message can be correctly decoded even if part of it is

obscured by interference. The code can be further complicated by such things as frequency diversity of transmission which would force the jammer to operate on several frequencies at once in correct sequence.

Since the mid-course guidance phase of the missile system appears to be the least vulnerable part, the complication which can be afforded to provide jamming protection is difficult to assess but probably no great complexity is justified. It appears likely that the largest gain for the smallest development effort would be obtained by the development of a valve capable of transmitting a very much higher level of mean power over short periods. This would have the further advantage that it would tend to simplify the missile rather than complicate it.

The present code requires a valve which is halfway between a radar type pulse generator and a C.W. generator. In general, pulse valves will not generate the mean power required as the duty cycle over the message is too high, and C.W. valve will not generate the peak power desirable.

5 Variations of the System

Two other single beacon mid-course guidance systems have been considered and have been the subject of work by Messrs. Ferranti.

One of these systems may be described as the pulsed beam system in which the rotating fan beam is pulsed to convey information instead of using a separate information channel. The missile extracts information from the beam modulation which allows it to deduce the angle between the sight line from the beacon to the missile and a reference bearing, the angle missile-beacon-target, and target height. Thus the information which the missile has is the same as that provided in this system except that its bearing from the beacon to a reference line is specified in each transmission. Work on this system is being carried out at the Wythenshawe laboratories of Messrs. Ferranti[3].

The London Computer Laboratories of Messrs. Ferranti, in examining digital data handling methods applied to missile guidance, have suggested a variation of this system and a C.W. beam, broadcast pulse system which in main features is very similar to the R.A.E. system.

All the Ferranti systems are based upon providing navigational information to the missile, to a quantum level of about 20 mins of arc whereas the R.A.E. system aims at providing this information to a quantum level of 3.5 mins of arc or 1 mil. This does not mean that the accuracy of the system will be as good as this, but only that it could be if the apparatus were perfect and there were no site on propagation problems. It is, however, regarded as important that the magnitude of the additional errors introduced should be determined experimentally and the limit of accuracy of this type of system established. This can only be done in a system where the quantum level is small enough. This fact alone is sufficient justification for the experimental programme projected by R.A.E.

The chief differences between the R.A.E. system and the Ferranti, London, C.W. beam system are that the techniques of data handling are different and that the information transmission is different. It is, however, unlikely that this section of Ferranti's will proceed further with the development of this system. There is less resemblance between the R.A.E. system and the Ferranti Wythenshawe system, in fact the only common factor is the use of a rotating fan beam and the intention that missiles should fly sight line courses. From the trials with the R.A.E. system a mass of data should be available which could be of help to

Messrs. Ferranti on the general problems of beacon design, particularly with regard to site effects affecting transmission, fading etc., methods of trials instrumentation and the mechanical and engineering problems of beacon transmitters.

References have been made in various places in this note to small variations in the system. The most significant of these is the suggestion that a data period of about 10 seconds might be acceptable which would enable the X band fan beam of the beacon to be replaced by the fan beam of the surveillance radar. This possibility introduces several difficulties in transmisssion but the saving of one transmitter consistutes an appreciable reduction in ground equipment and probably justifies some further complication in the data handling equipment. A system based upon the use of the radar beam in this way is being considered and will be the subject of a further note.

6 Further Development

In this section it is intended to list the items requiring further development to make this system available for operational use in missiles, but which will not be carried out in the G.W. Dept. R.A.E.

To complete the interception trial phase of the experimental programme (see Section 3.1) it will be necessary, to obtain target bearing in binary digital form, revised every 1/10th second. The target, in this trial, should be flown at a range of 50-100 miles and on the coastal site proposed at Band Hill, near Cromer, there is in existence a type 80 radar which could be used to obtain target plots. It would be desirable to be able to extract information on one target from this radar and to pass it to a single unit tracker and coder which could pass the information to the beacon in the correct form at the desired rate.

A fitting termination to the trials programme would be the demonstration of the complete interception course using a homing head or A.1 equipment mounted in the nose of the aircraft directed by the information transmitted by the mid-course guidance system. The engineering of the head or A.1. to give scan and acquisition characteristics representative of the S.A.G.W. homing head requires development and co-operation from outside sources.

The design of the operational missile system requires further consideration to be given to the information transmission system, an assessment of the jamming resistance economically desirable and some further valve developments to raise the power transmitted on both channels to a maximum. It has not been suggested that S and X bands are necessarily the correct frequencies for the operation of the system. It is probable that the optimum frequency lies somewhere between these two bands and this frequency has yet to be selected.

The largest item of development is in the data handling circuits. To minimise the size of the ground equipment it is logical to combine the ground radar tracking system and the beacon data handling equipment in one computor which incoporates the desirable characteristics of the data sampling mechanism as determined by simulator experiments. It is also necessary to develop and incorporate in this computor a simple missile simulator which will enable "rough" missile range to be obtained to determine the time at which height transmission should commence.

So far, insufficient consideration has been given to the problems of missile height programming, firing site layout and the problems of gathering. These items need to be resolved in some detail before the system can be considered suitable for use in an operational system.

Finally, little information has been made available on the effect of flame attenuation from the type of engine likely to be used in this missile. From the evidence available it appears likely that the effect of flame will probably not be serious but this cannot be checked until tests can be made on the actual motors likely to be used.

7 Conclusions

The completion of the experimental trials of this system of mid-course guidance will show whether the radio field required can be transmitted with sufficient accuracy for missile guidance, whether fading and propagation problems are likely to be serious, and whether the code transmission system used is likely to be satisfactory. In addition a considerable amount of practical experience will be accumulated on the problems of beacon construction and the associated electronic circuits required on the ground and in the missile.

As a result, the design of an operational system of missile mid-course guidance will be able to go forward on a sound basis, but considerable further development will be necessary on some of the more detailed aspects of the system. In particular, more attention must be given to the design of the data handling equipment on the ground, to the gathering phase problems and to the problems relating to the operation of the receiving equipment in a missile.

Schedule of Development

Item	Target Date
Completion of base mounting for aerials. (Final S band, interim X band).	January 1956
Modification of aircraft and mounting of equipment.	Start May 1956 Completion June 1956
Completion of ground equipment and erection on site. (Final S band, interim X band).	July 1956
Completion of base mounting final X band assembly.	July 1956
Completion and erection of final X band equipment. Completion of trials on interim equipment.	December 1956 January 1957
Completion of base mountings at coastal site.	January 1957
Completion of trials at Ewshot site.	June 1957
Transfer of trials to coastal site.	July 1957
Completion of trials at coastal site. End of investigation	December 1957

REFERENCES

(1) A single beacon method of mid-course guidance for a long range ground to air weapon.
R.A.E. Tech. Note No. G.W. 347
by S.E. Shapcott

(2) The application of digital methods to the guidance of Stage II Air Defence Missiles.
LCL No. 10
Ferranti London Computing Laboratories

(3) Twin beacon and single beacon systems of mid-course guidance.
Tech. Note No. 4018
Ferranti, Wythenshawe.

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Air Attache, London

23 March 1956

Royal Aircraft Establishment

January 1956

SPENCER G. MORGAN, Major, USAF
Asst to the Air Attache (Technical)

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(UNCLD) Single Beacon Mid-Course Guidance

1. Forwarded herewith as an inclosure to this report is R.A.E. Technical Note No. G.W.396 entitled "Single Beacon Mid-Course Guidance: Experimental Programme and Further Development" dated January 1956.

2. This Tech. Note describes the present status of the proposed method of mid-course guidance for long range ground-to-air missile that was described in R.A.E. Technical Note No. G.W. 347 forwarded by IR-203-55. The report proposes an experimental program to investigate the system by the use of aircraft flying in the guidance beam and having accurate photographic reference to ground position. The report further indicates development work necessary to render the system suitable for use in an operational missile.

COMMENTS OF THE PREPARING OFFICER:

3. The development work of this guidance system is being done by Ferranti Limited who in conjunction with the Bristol Airplane Company are undertaking a long range development program for the missile defense system of the U.K. known as Stage 2 and planned for the era 1963-65. The principles of this system were set forth in Ferranti Limited Technical Note No. 4018 entitled "Twin Beacon and Single Beacon Systems of Mid-Course Guidance" dated May 1955. This report should be available at ASTIA.

4. The number of copies of the inclosure to this report that have been made available to this office has been limited due to the contents, as was the case of Tech. Note No. G.W.347. Therefore, the normal automatic distribution to ASTIA, DCS/D, ARDC, WADC, RADC, AFCRC, AFMTC and HADC cannot be accomplished. It is suggested that some scheme of shared distribution be worked out.

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